# 12 The First Law of Thermodynamics

> **KEY IDEA**
>
> The change in internal energy of a system is the difference between the heat added to the system and the work done by the system; thus mechanical energy is conserved.

## PHYSICS AROUND US . . . The Great Circle of Energy

A few days ago you may have gone to your local gas station and filled up the tank of your car with gasoline. Have you ever wondered where that gasoline came from?

Hundreds of millions of years ago, a bit of energy was liberated from the incandescent core of the Sun. For thousands of years, that energy traveled outward to the Sun's surface. Then, in a mere 8 minutes, that energy made the trip through empty space to Earth in the form of sunlight, where it was absorbed by organisms known as algae floating on the warm ocean surface.

Through a process known as *photosynthesis,* the algae transformed the Sun's energy into the chemical energy of its complex molecules. Eventually the algae died and sank to the bottom of the ocean, where over millions of years those molecules were buried deeper and deeper. Under the influence of pressure and heat, the molecules were eventually transformed into energy-rich fossil fuel—petroleum.

Then, a short while ago, engineers pumped that petroleum with its stored chemical energy up out of the ground. At a refinery, the large molecules were broken down into gasoline and other compounds, and the gasoline was shipped to your town. The last time you drove you burned that gasoline, converting the stored energy into the engine's mechanical energy that moved your car.

What's remarkable about this story is that the mechanical energy and heat produced when your car burned that gasoline is exactly the same energy that was released by the Sun hundreds of millions of years ago. One of the great discoveries of physics is that energy can change forms many times over vast stretches of time, but the total amount of energy is constant.

# THE MANY FORMS OF ENERGY

In Chapter 8 we introduced the notion of energy as the ability to do work or to exert a force over a distance. We discussed two kinds of energy—kinetic energy (or energy of motion) and gravitational potential energy (energy associated with being located at some height in a gravitational field). We saw that for these two types of mechanical energy (neglecting friction) two important principles hold. First, the energy of a system can change back and forth between these two forms, and, second, the total amount of kinetic and gravitational potential energy in an isolated system has to remain fixed.

In this chapter we examine many additional forms of energy other than mechanical energy. Despite this diversity in forms, however, the two general principles still hold: one form of energy can always be transformed into another, and the total amount always stays the same. As a result, we can extend conservation of energy to chemical systems and biological systems—to any system at all. In fact, in thermodynamics, we can define a *system* to be any collection of objects we're talking about, from engines to organisms, from molecules to galaxies. The principles of energy apply to all of them.

## Heat as a Form of Energy

Energy, the ability to do work, appears in all natural systems and comes in many forms (Table 12-1). Two centuries ago scientists understood the behavior of kinetic and potential energy, but the nature of heat was far more elusive. We've seen that atoms and molecules—the tiny particles that make up all matter—move around and vibrate and, therefore, particles possess kinetic energy. Only other atoms and molecules experience the minuscule forces they exert, but that small scale doesn't make the force any less real. If molecules in a material move more rapidly, they have more kinetic energy and are capable of exerting greater forces on each other in collisions. If you touch an object whose molecules are moving fast, the collisions of those molecules with molecules in your hand exert greater force than if they were moving slowly, and you perceive the object to be hot. What we normally call *heat,* therefore, is simply a transfer of *thermal energy*—the kinetic energy of atoms and molecules. As we point out in Chapter 11, it's important to remember that the term *heat* should be used only to refer to thermal energy in the process of being transferred from one object to another due to a temperature difference.

**TABLE 12-1 Kinds of Energy**

| Potential Energy | Kinetic Energy |
|---|---|
| Gravitational | Moving objects |
| Chemical | Thermal |
| Elastic | Sound and other mechanical waves |
| Electromagnetic | |
| Mass | |

## Potential Energies

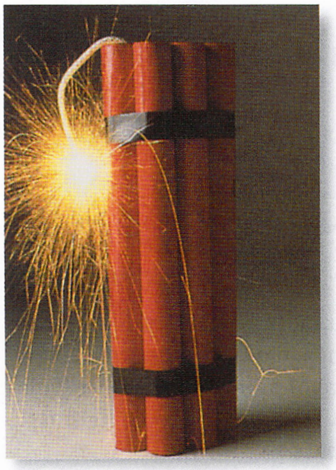
As we discussed in Chapter 8, potential energy is stored energy. In our daily lives we encounter many other kinds of potential energy in addition to the gravitational kind. Chemical potential energy is stored in the gasoline that moves your car, the batteries that power your radio, and the food you eat. All animals depend on the chemical potential energy of food, and all living things rely on molecules that store chemical energy for future use. In each of these situations, potential energy is stored in the chemical bonds between atoms (see Chapter 23).

Wall outlets in your home and at work provide a means to tap into electric potential energy, available to turn a fan or drive a vacuum cleaner. We see in Chapter 18 that electric potential energy depends on an electric field, just the way gravitational potential energy depends on a gravitational field.

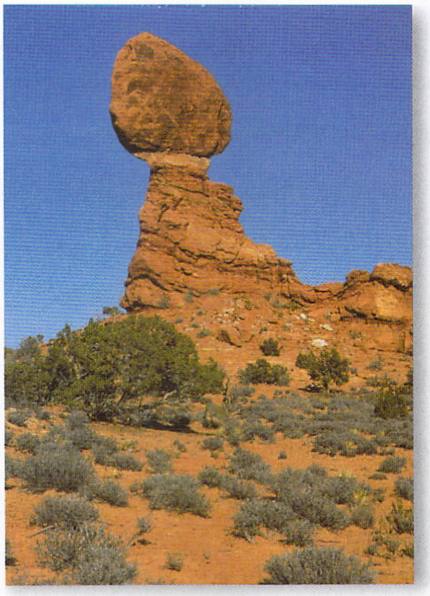
In some situations, such as a tightly coiled spring, a flexed muscle, or a stretched rubber band, a different kind of energy is stored in the bonds between atoms. In these materials, work must be done to bring them to the energetic state we have described (for example, you have to exert a force over a distance to stretch a rubber band). This energy is stored in the chemical bonds and can be released when the situation is right (for example, when you let go of the rubber band). We say that these materials can contain elastic potential energy.

A refrigerator magnet holding a note in your kitchen carries magnetic potential energy. You have to exert a net force over a distance to remove the magnet from the refrigerator, and a net force is exerted over a distance on your hand when you put it back.

No matter which form the potential energy takes, however, in each case energy is stored, ready to do work.



(a)



(b)

(c)

Potential energy comes in many forms. (*a*) Explosives with a lighted fuse contain chemical potential energy. (*b*) A rock ready to fall possesses gravitational potential energy. (*c*) A drawn bow has elastic potential energy. All are examples of potential energy about to be converted into other forms.

Waves possess a form of kinetic energy.

## Energy in Waves

Anyone who has watched surf battering a seashore knows that waves carry energy. In the case of water waves, large volumes of water are in motion and therefore possess kinetic energy. It is this energy that we see released when waves hit the shore. Other kinds of waves also possess energy (see Chapters 14 and 15). For example, when a sound wave is generated, molecules in the air are set in motion and the energy of the sound wave is associated with the kinetic energy of those molecules. When the energy of the wave reaches our ears, we hear sound. In Chapter 19 we will meet another important kind of wave, the kind associated with electromagnetic radiation, such as the radiant energy (light) that streams from the Sun. This sort of wave stores its energy in changing electric and magnetic fields.

## Mass as Energy

The discovery that certain atoms, such as uranium, spontaneously release energy as they disintegrate—the phenomenon of radioactivity—led to the realization in the early twentieth century that mass is a form of energy. This principle is the focus of Chapter 28, but the main idea is summarized in Albert Einstein's most famous equation.

**1.** In words:

*Every object at rest contains potential energy equivalent to the product of its mass times a constant, which is the speed of light squared.*

**2.** In an equation with words:

$$\text{Energy (joules)} = \text{Mass (kg)} \times [\text{Speed of light (m/s)}]^2$$

**3.** In an equation with symbols:

$$E = mc^2$$

where $c$ is the symbol for the speed of light, a constant equal to about 300,000,000 meters per second ($3 \times 10^8$ m/s).

This equation, which has achieved the rank of a cultural icon, tells us that it is possible to change energy into mass and to change mass into energy. (Note: This equation does not mean the mass has to be traveling at the speed of light; the mass is assumed to be at rest.) Furthermore, because the speed of light is so great, the energy stored in even a tiny amount of mass is enormous.

### Lots of Potential

EXAMPLE 12-1

According to Einstein's equation, how much potential energy is contained in the mass of a 1-gram grape sitting on your desk?

**REASONING AND SOLUTION:** Substitute the mass, 1 g, into Einstein's equation. Remember that a gram is 1 thousandth of a kilogram and the speed of light is a constant, $3 \times 10^8$ m/s.

$$\begin{aligned}\text{Energy (joules)} &= \text{Mass (kg)} \times [\text{Speed of light (m/s)}]^2 \\ &= 0.001 \text{ kg} \times (3 \times 10^8 \text{ m/s})^2 \\ &= 0.001 \times (9 \times 10^{16} \text{ kg-m}^2/\text{s}^2) \\ &= 9 \times 10^{13} \text{ joules}\end{aligned}$$

The energy contained in a mass of 1 gram is prodigious: almost 100 trillion joules, which is 25 million kilowatt-hours. The average American family uses about 1000 kilowatt-hours of electricity per month, so a single grape—if we had the means to convert its mass entirely to electric energy (which we don't)—could satisfy your home's energy needs for the next 2000 years!

In practical terms, Einstein's equation showed that mass could be used to generate electricity in nuclear power plants in which a few pounds of nuclear fuel is enough to power an entire city. ●

## THE INTERCHANGEABILITY OF ENERGY

You know from everyday experience that energy can transform from one kind to another. Plants absorb light streaming from the Sun and convert that radiant energy into the stored chemical energy of their cells. You eat plants and convert the chemical energy into the kinetic energy of your muscles—energy of motion that in turn can be converted into gravitational potential energy when you climb a flight of stairs, elastic potential energy when you jump in the air, or heat when you rub your hands together (Figure 12-1). The lesson from these examples is clear:

*The many different forms of energy are interchangeable.*

Bungee jumping provides a dramatic illustration of this rule (Figure 12-2, page 256). A bungee jumper climbs to a high bridge or platform, where an elastic cord is attached to an ankle. Then the jumper launches out into space and falls toward the ground until the cord stretches, slows the jumper down, and stops the fall.

From an energy point of view, a bungee jumper uses the chemical potential energy generated from food to walk up to the launching platform. The work that had been done against gravity to reach the launching platform provides the jumper with gravitational potential energy. During the long descent, the gravitational potential energy diminishes while the jumper's kinetic energy simultaneously increases. As the cord begins to stretch, the jumper slows down and kinetic energy is converted (gradually) to stored elastic potential energy in the cord. Eventually, the gravitational potential energy that the jumper had at the beginning is completely transferred to the stretched elastic cord. The cord then rebounds, converting some of the stored elastic energy back into kinetic energy and gravitational potential energy. All the time, some of the energy is also converted to heat, which increases the thermal energy of materials: thermal energy in the stressed cord, thermal energy due to friction on the jumper's ankles, and thermal energy in the air as it is pushed aside.

**FIGURE 12-1.** A pole-vaulter uses the energy of food to power his muscles for running. Kinetic energy of running is converted into elastic potential energy of the bent pole. That elastic potential energy converts to kinetic energy, giving the skilled vaulter sufficient gravitational potential energy to clear the bar.

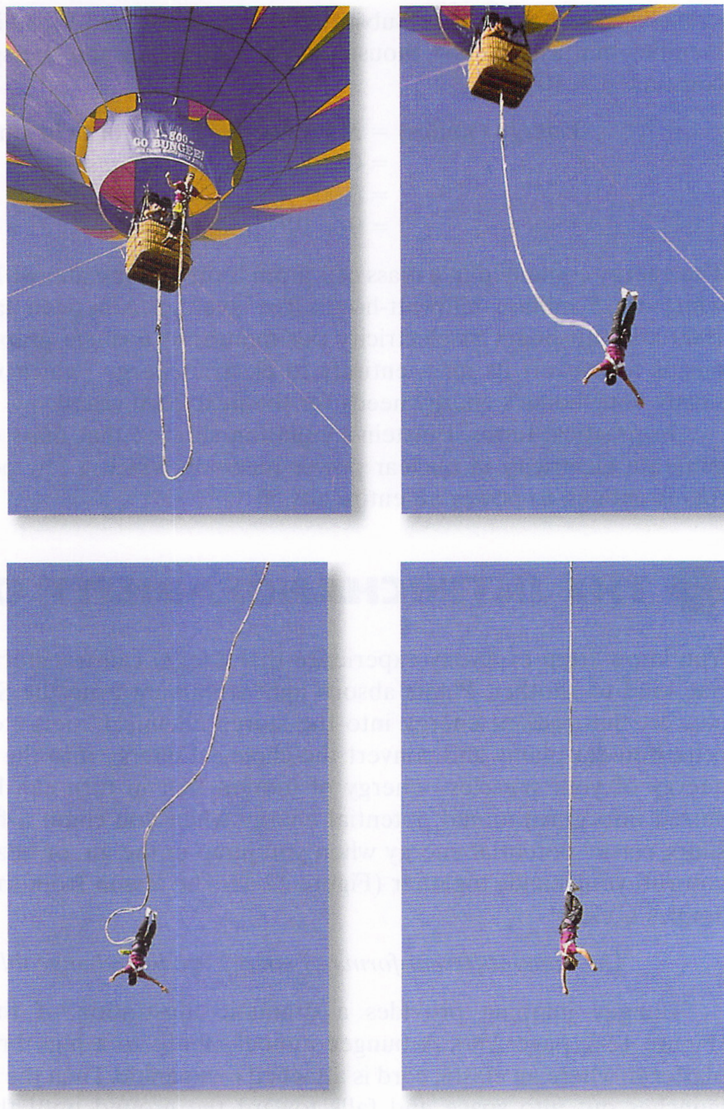


**FIGURE 12-2.** Bungee jumping provides a dramatic example of energy changing from one form to another. Can you identify points at which the jumper has maximum kinetic energy? Maximum gravitational potential energy? Maximum elastic potential energy? Does the jumper ever have a combination of all three? What other kinds of energy are involved?

One of the most fundamental properties of the universe in which we live is that, theoretically, every form of energy on our list (Table 12-1) can be converted to every other form of energy.

## Ongoing Process of Science

### New Sources of Energy

The realization that energy can shift from one form to another drives many scientists to search for new energy-gathering technologies. For thousands of years humans have used sunlight to grow crops, wind to propel their ships, and waterfalls to turn their millstones. Energy from blowing wind, falling water, and brilliant sunlight is still all around us, just waiting to be used, if only we had the practical means to convert it cheaply and efficiently into electricity. Given society's incessant and growing demand for energy, research on new sources of energy continues to be a major scientific enterprise.

The National Renewable Energy Laboratory in Golden, Colorado, is one of the largest North American centers for this kind of research. This state-of-the-art facility, operated with about a quarter-billion tax dollars per year, is home to more than 1000 scientists, engineers, and support staff. Among the laboratory's most successful efforts is the development of novel photovoltaic materials, which are the increasingly familiar black wafers or foils that convert sunlight directly to electric energy in many objects, from roadside signs to pocket calculators.

A more exotic energy technology is being explored at the National Ignition Facility at California's Lawrence Livermore National Laboratory. There, a formidable array of 192 powerful lasers, each capable of blasting a hole through a cinder-block wall, is being constructed to focus on a BB-size pellet of hydrogen fuel. The resulting burst of energy will create, for a brief moment, a miniature sun that radiates intense heat and light as a portion of the hydrogen's mass is converted into energy (see Chapter 26). If all goes as planned, the lasers will fire in unison sometime early in the twenty-first century.

No one can predict how useful energy will be produced a century from now, but one thing is certain. Society will always need energy, and scientists will continue to ask how it can be harnessed. ●

## ENERGY AND LIVING SYSTEMS: TROPHIC LEVELS

The concept of energy has been useful in areas of science other than physics. In chemistry, energy is one of the key criteria in determining whether a given reaction will take place. In biology, energy helps determine how an organism functions and how systems of organisms interact with the environment and with one another.

All of Earth's systems, both living and nonliving, transform the Sun's radiant energy into other forms. Just how much energy is available, and how is it used by living organisms? At the top of Earth's atmosphere, the Sun's incoming energy is about 1400 watts per square meter. To calculate the total solar energy we receive, we first need to calculate the cross-sectional area of the Earth in square meters (Figure 12-3*a*, page 258). The radius of the Earth is 6375 kilometers (6,375,000 meters), so the cross-sectional area is

$$\begin{aligned}\text{Area of a circle} &= \text{Pi} \times (\text{radius})^2 \\ &= 3.14 \times (6{,}375{,}000\ \text{m})^2 \\ &= 1.28 \times 10^{14}\ \text{m}^2\end{aligned}$$

Thus the total power received at the top of Earth's atmosphere is

$$\begin{aligned}\text{Power} &= \text{Solar energy per m}^2 \times \text{Earth's cross-sectional area} \\ &= 1400\ \text{watts/m}^2 \times 1.28 \times 10^{14}\ \text{m}^2 \\ &= 1.79 \times 10^{17}\ \text{watts (or joules/second)}\end{aligned}$$

Each second, the top of Earth's atmosphere receives $1.79 \times 10^{17}$ joules of energy, but less than half that amount reaches the ground (Figure 12-3*b*). When solar radiation encounters the top of the atmosphere, about 25% of it is immediately reflected back into space. Another 25% is absorbed by gases in the atmosphere, and Earth's surface reflects an additional 5% back into space. These processes leave about 45% of the initial amount to be absorbed at the Earth's surface.

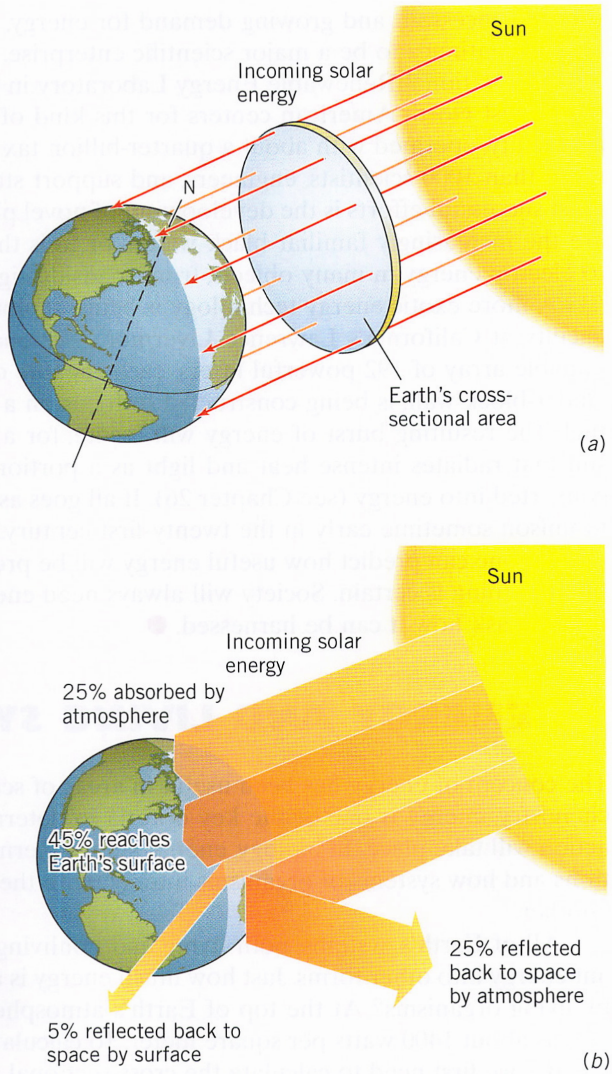



**FIGURE 12-3.** (*a*) The Sun illuminates Earth with a large amount of energy crossing through the Earth's cross-sectional area. (*b*) Much of this incoming energy does not reach Earth's surface.

All living systems take their energy from this 45%, but absorb only a small portion of this amount—only about 4% to run photosynthesis and supply the entire food chain. A much larger portion heats the ground and air or evaporates water from lakes, rivers, and oceans. This energy is all radiated back into space eventually.

To track the many changes of energy as it flows through the living systems of Earth, the concept of the food chain and its trophic levels is particularly useful. A **trophic level** consists of all organisms that get their energy from the same source (Figure 12-4). In this ranking scheme, all plants that produce energy from photosynthesis are in the first trophic level. These plants all absorb energy from sunlight and use it to drive chemical reactions that make plant tissues and other complex molecules. These plant tissues are subsequently used as energy sources by organisms in higher trophic levels.

The second trophic level includes all herbivores—animals that get their energy by eating plants of the first trophic level. Cows, rabbits, and many insects occupy this level. The third trophic level, as you might expect, consists of

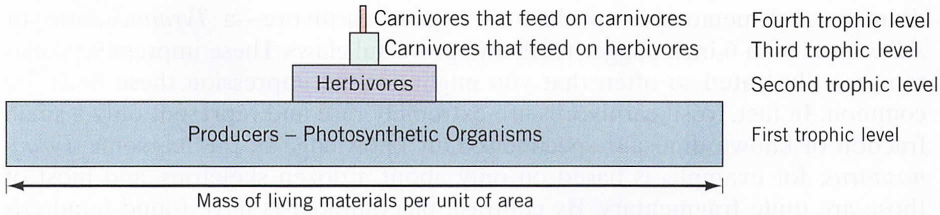



**FIGURE 12-4.** Living organisms are arranged in trophic levels according to how they obtain energy. The first trophic level consists of plants that produce energy from photosynthesis. In the higher trophic levels, animals get their energy by feeding on organisms from the next lowest level.

carnivores—animals that get their energy by eating organisms in the second trophic level. This third level includes such familiar animals as wolves, eagles, and lions, as well as insect-eating birds, blood-sucking ticks and mosquitoes, and many other organisms.

A few more groups of organisms fill out the scheme of trophic levels on the Earth. Carnivores that eat other carnivores, such as killer whales, occupy the fourth trophic level. Termites, vultures, and a host of bacteria and fungi get their energy from feeding on dead organisms and are generally placed in a trophic level separate from the four we've just described. (The usual convention is that this trophic level is not given a number because the dead organisms can come from any of the other trophic levels.)

Several species of animals and plants span the trophic levels. Humans, raccoons, and bears, for example, are omnivores that gain energy from plants and from organisms in other trophic levels, while the Venus flytrap supplements its diet with trapped insects.

Although you might expect it to be otherwise, the efficiency with which solar energy is used by Earth's organisms is very low, despite the struggle by all these organisms to use energy efficiently. For example, when sunlight falls on a cornfield in the middle of Iowa in August, arguably one of the best situations in the world for plant growth, only a small percentage of the solar energy striking the field is actually transformed as chemical energy in the plants. All the rest of the energy is reflected, heats up the soil, evaporates water, or performs some other function. It is a general rule that no plants anywhere transform as much as 10% of the solar energy available to them.

The same situation applies to trophic levels above the first. Typically, less than 10% of a plant's chemical potential energy winds up as tissue in an animal of the second trophic level that eats the plants. That is, less than about 1% (10% of 10%) of the original energy in sunlight is transformed into chemical energy of the second trophic level. Continuing with the same pattern, animals in the third trophic level also use less than 10% of the energy available from the second level.

You can do a rough verification of this statement in your supermarket. Whole grains (those that have not been processed heavily) typically cost about one-tenth as much as fresh meat. Examined from an energy point of view, this cost differential is not surprising. It takes 10 times as much energy to make a pound of beef as it does to make a pound of wheat or rice, and this fact is reflected in the price.

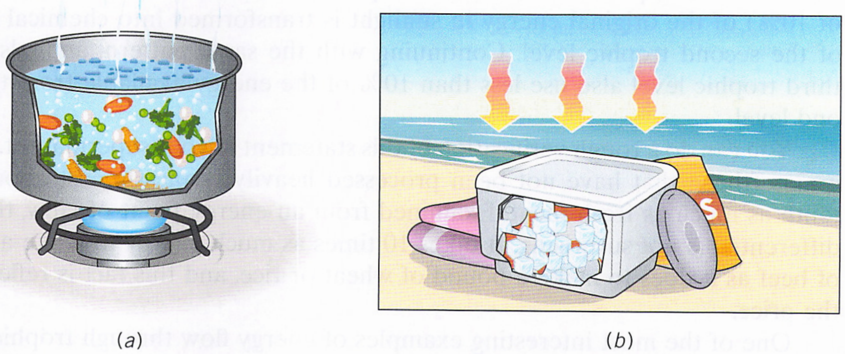
One of the most interesting examples of energy flow through trophic levels can be seen in the fossils of dinosaurs. In many museum exhibits, the most dramatic and memorable specimen is a giant carnivore—a *Tyrannosaurus* or *Allosaurus* with 6-inch dagger teeth and powerful claws. These impressive skeletons are illustrated so often that you might get the impression these finds are common. In fact, fossil carnivores are extremely rare and represent only a small fraction of known dinosaur specimens. Our knowledge of the fearsome *Tyrannosaurus,* for example, is based on only about a dozen skeletons, and most of those are quite fragmentary. By contrast, paleontologists have found hundreds of skeletons of plant-eating dinosaurs. This distribution is hardly chance. Carnivorous dinosaurs, like modern lions and tigers, were relatively scarce compared to their herbivorous victims. In fact, statistical studies of all dinosaur skeletons reveal a roughly 10:1 herbivore-to-carnivore ratio, a value approaching what we find today for the ratio of warm-blooded herbivores to warm-blooded carnivores, and much higher than the herbivore-to-carnivore ratio observed in modern cold-blooded reptiles. Many paleontologists cite this pattern as evidence that dinosaurs were warm-blooded.

## THE FIRST LAW OF THERMODYNAMICS: HEAT, WORK, AND INTERNAL ENERGY

We have emphasized several times that energy is a fundamental concept of importance in all areas of science and technology. One reason why this is so is that conservation of energy applies in all these various forms and applications of energy. The general statement of energy conservation that applies to a system under consideration is called the *first law of thermodynamics.*

Before describing the first law, we must first think about the idea of a thermodynamic system. You can think of a **system** as an imaginary box into which you put some matter and some energy that you'd like to study. Scientists might want to study a system containing only a pan of water or perhaps a system consisting of a forest or even the entire planet Earth. Doctors examine your nervous system, astronomers explore the solar system, and biologists observe a variety of ecosystems. In each case, the investigation of nature is simplified by focusing on one small part of the universe.

If the system under study can exchange matter and energy with its surroundings—for example, a pan full of water that is heated on a stove and gradually evaporates—then it is an *open* system (Figure 12-5*a*). An open system is



(a) (b)

**FIGURE 12-5.** (*a*) Boiling vegetables in a pot without a lid is an open system (heat and matter can flow in or out). (*b*) A closed Styrofoam cooler is an isolated system (no heat or matter can enter or leave the system).

like an open box where you can take things out and put things back in. Alternatively, if a system can exchange energy but not matter with its surroundings—for example, a tightly shut box made of heat-conducting material—the system is a *closed* system (Figure 12-5*b*). If the system can exchange neither matter nor energy with its surroundings—for example, a tightly shut box made of insulating material—the system is an *isolated* system. Earth and its primary source of energy, the Sun, together make a system that may be thought of for most purposes as isolated because there are no significant amounts of matter or energy being added from outside sources.

The first law of thermodynamics is a relationship among heat, work, and internal energy for a closed system. We've already defined "heat" as a transfer of energy into or out of a system and "internal energy" as the sum of the average kinetic energies of the particles of a system. For these purposes, work involves the motion of a system or part of a system in response to a net applied force. For example, a cylinder with a piston, as you can find in any internal combustion engine (in your car, say), does work when the gas in the cylinder expands, pushing the piston out. If you push the cylinder in, you're doing work on the system, instead of the system doing the work.

We're now ready to state the **first law of thermodynamics.**

**1.** In words:

*In a closed system, the change in internal energy depends on the heat added to the system and the work done by the system.*

**2.** In an equation with words:

Change in internal energy equals heat added minus work done (for a closed system).

**3.** In an equation with symbols:

$$\Delta U = Q - W$$

where $U$, $Q$, and $W$ stand for internal energy, heat, and work, respectively.

As an example of the first law, consider the engine of your car. It has all kinds of gears and electrical connections; we won't worry about those. Instead, let's take as our system one cylinder with its piston. A mixture of air and gasoline enters the cylinder, is ignited by a spark, and expands, pushing the piston. We want to look at the closed system when the mixture is ignited and the gas is expanding—that is, when the heat is generated and the work is done. What the first law of thermodynamics says is that the work done by the piston is limited. The engine can do only as much work as there is energy available in the form of internal energy and added heat. Intuitively, this makes sense: you can't get energy out of nothing. To make the engine do work, you have to supply heat, in the form of burning fuel. Now, if you have an electric car, you can supply electric energy from a battery to make the engine do work. As far as the first law is concerned, that's fine, but the energy balance is still the same—you have to supply energy to get work done.

Energy is something like an economy with an absolutely fixed amount of money. You can earn it, store it in a bank or under your pillow, and spend it here and there when you want to. But the total amount of money doesn't change just because it passes through your hands. Likewise, in any physical situation, you can shuffle energy from one place to another. You can take it out of the account labeled "kinetic" and put it into the account labeled "potential;" you can spread it around into accounts labeled "chemical potential," "elastic potential," "heat," and so on. However, the first law of thermodynamics tells us that, in a closed system, you can never have more energy than you started with.

LOOKING DEEPER

# Diet and Calories

The first law of thermodynamics has a great deal to say about the American obsession with weight and diet. Human beings take in energy with their food, energy we usually measure in Calories. (Note that the "Calorie" we talk about in foods is defined as the amount of energy needed to raise the temperature of 1 kilogram of water 1°C, a unit we call a "kilocalorie" in Chapter 11.) Let's consider our body as the system of interest. When a certain amount of energy is taken in, the first law says that only one of two things can happen to it: it can be used to do work and generate waste heat or it can be stored as internal energy. If we take in more energy than we expend, the excess is stored as chemical potential energy in the form of body fat. If, on the other hand, we take in less than we expend, energy must be removed from storage to meet the deficit, and the amount of body fat decreases.

Here are a couple of rough rules you can use to calculate how many Calories should be in your diet:

1. Under most circumstances, normal body maintenance uses up about 15 Calories per day for each pound of body weight.
2. You must consume about 3500 Calories to gain 1 pound of body fat.

Suppose you weigh 150 pounds. To keep your body weight constant, you have to take in

150 pounds × 15 Calories/pound
= 2250 Calories per day

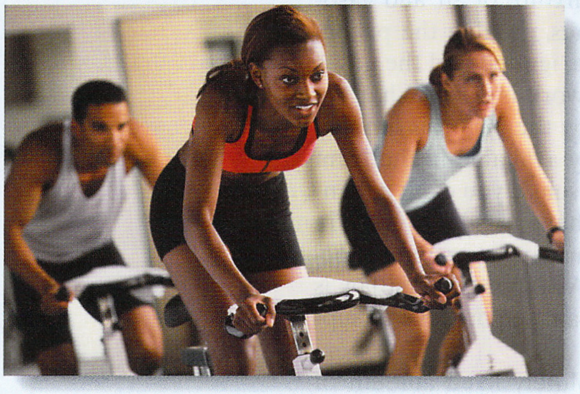


**FIGURE 12-6.** Different kinds of physical activity use different amounts of energy.

**TABLE 12-2 Calories Burned in 10 Minutes of Exercise (150-lb person)**

| Activity | Calories |
|---|---|
| Volleyball | 34 |
| Walking (3 mph) | 40 |
| Bicycling (5.5 mph) | 47 |
| Calisthenics | 49 |
| Golf | 54 |
| Skating (moderate) | 54 |
| Walking (4 mph) | 58 |
| Tennis | 68 |
| Canoeing (4 mph) | 70 |
| Swimming (breaststroke) | 72 |
| Bicycling (10 mph) | 81 |
| Swimming (crawl) | 87 |
| Jogging (11 min-mile) | 91 |
| Handball/Racquetball | 95 |
| Skiing (downhill) | 95 |
| Mountain climbing | 100 |
| Skiing (cross-country) | 108 |
| Running (8 min-mile) | 141 |

If you want to lose 1 pound (3500 Calories) in a week (7 days), you have to reduce your daily Calorie intake by

$$\frac{3500 \text{ Calories}}{7 \text{ days}} = 500 \text{ Calories per day}$$

Another way of saying this is that you have to reduce your Calorie intake to 1750 Calories—the equivalent of skipping dessert every day.

Alternatively, the first law says you can increase your energy use through exercise. Roughly speaking, to burn off 500 Calories you have to run 5 miles, bike 15 miles, or swim for 1 hour (see Figure 12-6 and Table 12-2). It's a whole lot easier to refrain from eating than to burn off the weight by exercise. In fact, most researchers now say that the main benefit of exercise in weight control has to do with its ability to help people control their appetites.

### Develop Your Intuition: Working off Dessert

Your friend weighs 155 lb (mass of 70 kg) and doesn't want to gain more weight. However, he decides to celebrate an A on the physics test by having a hot fudge sundae with whipped cream (900 Calories) and then working off the calories by climbing up several flights of stairs. How high would he have to climb to burn off this dessert?

Fat in the body is a form of internal energy, so we want that to remain the same. From the first law, $\Delta U = 0 = Q - W$ or $Q = W$. That is, the work of climbing the stairs must equal the heat generated by eating the dessert, which we know is 900 Calories, or 900 kilocalories. We use the conversion factor that 1 kcal equals 4190 joules and get

$$Q = 900 \text{ kcal}\left(\frac{4190 \text{ J}}{1 \text{ kcal}}\right) = 3.77 \times 10^6 \text{ J}$$

This must equal the work done in climbing stairs, which equals *mgh,* where *m* is your friend's mass, *g* is the acceleration due to gravity, and *h* is the height we want to find (see Chapter 8). So we have

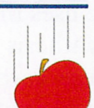
$$h = \frac{Q}{mg} = \frac{3.77 \times 10^6 \text{ J}}{(70 \text{ kg})(9.8 \text{ m/s}^2)}$$

$$= \frac{3.77 \times 10^6 \text{ J}}{686 \text{ N}} = 5500 \text{ meters (about 18,000 feet)}$$

He might be better off settling for a bowl of fruit after all.

## Physics in the Making

### Lord Kelvin and the Age of the Earth



The first law of thermodynamics provided physicists with a powerful tool for describing and analyzing the universe. Every isolated system, the law tells us, has a fixed amount of energy. Naturally, one of the first systems that scientists considered was the Earth and the Sun.

British physicist William Thomson (1824–1907), knighted in 1892 as Lord Kelvin, asked a simple question: How much energy could be stored in the Earth? Then, given the present rate at which energy radiates out into space, how old might the Earth be? Although simple, these questions had profound implications for philosophers and theologians who had their own ideas about Earth's relative

William Thomson, Lord Kelvin (1824–1907).

antiquity. Some Biblical scholars believed that the Earth could be no more than a few thousand years old. Most geologists, on the other hand, saw evidence in layered rocks to suggest the Earth was at least hundreds of millions of years old. Biologists also estimated that vast amounts of time were required to account for the gradual evolution of life on Earth. Who was correct?

Kelvin believed, as did most of his contemporaries, that the Earth had formed from a contracting cloud of interstellar dust. He thought that the Earth began as a hot body because impacts of large objects on it early in its history must have converted huge amounts of gravitational potential energy into heat. He used new developments in mathematics to calculate how long it had taken for the hot Earth to cool to its present temperature. He assumed that there were no sources of energy inside the Earth and found that the age of the Earth had to be much less than 100 million years. He soundly rejected the geologists' and biologists' claims of an older Earth because these claims seemed to violate the first law of thermodynamics.

Seldom have scientists come to such a bitter impasse. Two competing theories about the age of the Earth, each supported by seemingly sound observations, were at odds. The calculations of the physicist seemed unassailable, yet the observations of biologists and geologists in the field were equally meticulous. What could possibly resolve the dilemma? Had the scientific method failed?

The solution came from a totally unexpected source when scientists discovered in the 1890s that rocks hold a previously unknown source of energy, radioactivity, in which heat is generated by the conversion of mass. Lord Kelvin's rigorous age calculations were in error only because he and his contemporaries were unaware of this critical component of Earth's energy budget. The Earth, we now know, gains approximately half of its internal energy from the energy of radioactive decay. Revised calculations suggest an Earth several billions of years old, in conformity with geological and biological observations.

**THINKING MORE ABOUT**

## Energy: Fossil Fuels

All life is rich in the element carbon, which plays a key role in virtually all the chemicals that make up our cells. Life uses the Sun's energy, directly through photosynthesis or indirectly through food, to form these carbon-based substances that store chemical potential energy. When living things die, they may collect in layers at the bottoms of ponds, lakes, or oceans. Over time, as the layers become buried, Earth's temperature and pressure may alter the chemicals of life into deposits of fossil fuels.

Fossil fuels, carbon-rich deposits of ancient life that can burn with a hot flame, have been the most important energy source during the past century and a half. Coal, oil (petroleum), and natural gas, the most common fossil fuels, are consumed in prodigious quantities around the world (Figure 12-7). They now account for approximately 90% of all energy consumed by industrial nations. In the United States alone, approximately 1 billion tons of coal and 2.5 billion barrels of petroleum are used every year.

Geologists estimate that it takes tens of millions of years of gradual burial under layers of sediments, combined with the transforming effects of temperature and pressure, to form a coal seam or petroleum deposit. Coal forms from layer upon layer of plants that thrived in vast ancient swamps, while petroleum represents primarily the organic matter once contained in algae, microscopic organisms that float near the ocean's surface. While these natural processes continue today, the rate of

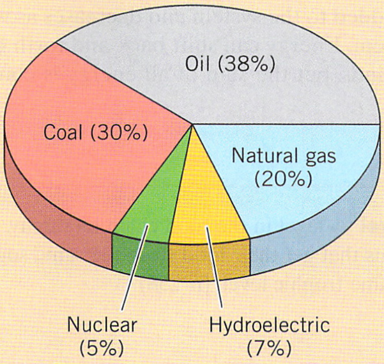
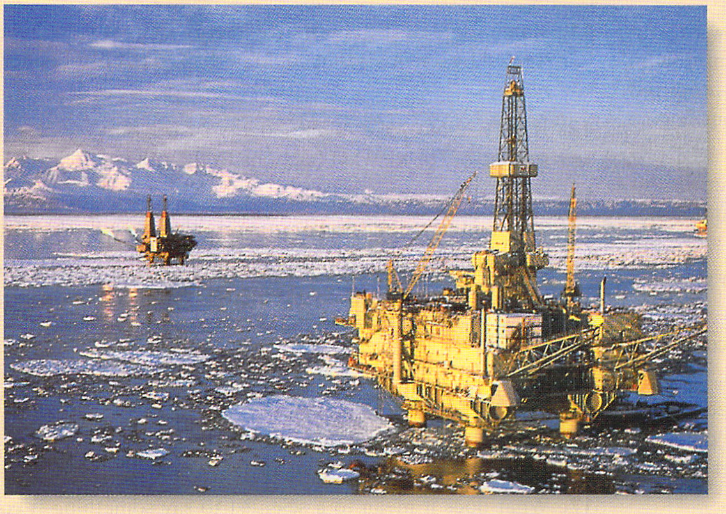



**FIGURE 12-7.** Sources of energy for industry. Note that most of our energy comes from fossil fuel.

coal and petroleum formation in Earth is only a small fraction of the fossil fuels being consumed. For this reason, fossil fuels are classified as nonrenewable resources.

One consequence of this situation is clear. Humans cannot continue to rely on fossil fuels forever. Reserves of high-grade crude oil and the cleanest-burning varieties of coal may last less than 100 more years. Less efficient forms of fossil fuels, including lower grades of coal and oil shale (in which petroleum is dispersed through solid rock), could be depleted within a few centuries. All the energy now locked up in those valuable energy reserves will still exist, but in the form of unusable heat radiating far into space.

Given the irreversibility of burning up our fossil fuel reserves, what steps should we take to promote energy conservation? As a concerned citizen, would you vote to tax energy at a higher rate? Would you support government funding for research and development of new energy sources? Do you think alternative energy sources such as wind and solar power will be able to replace fossil fuels in 100 years? These questions all come back to the first law of thermodynamics: You can't get work without supplying energy.



About 90% of the energy in industrialized nations comes from fossil fuels such as petroleum.

## Summary

Energy comes in several forms. Kinetic energy is the energy associated with moving objects such as cars or cannonballs. Potential energy, on the other hand, is stored, ready-to-use energy, such as the chemical energy of coal, the elastic energy of a coiled spring, the gravitational energy of dammed-up water, or the electric energy in your wall socket. Thermal energy or internal energy is a form of kinetic energy associated with vibrating atoms and molecules. Energy can also be transmitted by waves, such as sound waves or light waves. And early in the twentieth century it was discovered that mass is also a form of energy. All around us energy constantly shifts from one form to another, and all of these kinds of energy are interchangeable.

Photosynthetic plants in the first **trophic level** use energy from the Sun. These plants provide the energy for animals in higher trophic levels. Roughly speaking, only about 10% of the energy available at one trophic level finds its way to the next.

The most fundamental idea about energy, expressed in the **first law of thermodynamics,** is that it is conserved: the total amount of internal energy in a closed **system** increases as heat is added to the system and decreases as work is done by the system. Energy can shift back and forth between the different kinds, but the sum of all energy is constant.

## Key Terms

**first law of thermodynamics** The law of physics that states the relationship between heat, work, and changes in the internal energy of a closed system. (p. 261)

**system** A collection of matter and energy that is controlled in such a way that its physical properties can be studied; systems can be open, closed, or isolated. (p. 260)

**trophic level** A level in the food chain hierarchy. All organisms that get their food from the same source belong to the same trophic level. (p. 258)

## Key Equations

Energy associated with mass at rest (joules) = Mass (kg) × [Speed of light (m/s)]$^2$

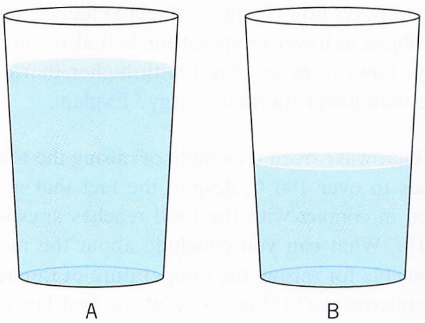
First Law of Thermodynamics: $\Delta U = Q - W$

## Review

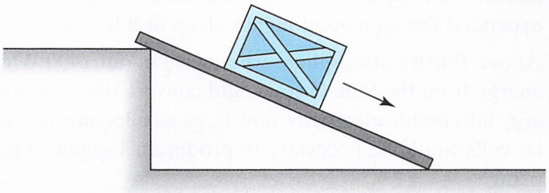
1. Where did all the energy in the gasoline that powers your car come from? What was the role of photosynthesis in generating this energy? Where does the energy produced as waste heat in your car engine go to when your engine cools down? Is it lost completely?
2. What are some of the forms of energy discussed in this chapter? What are the two general principles that hold for all forms of energy?
3. What is heat? Describe the relationship between heat and kinetic energy.
4. What is thermal energy? What is the difference, if any, between thermal energy and heat?
5. What types of potential energy were mentioned in this chapter? What is the relationship between any potential energy and the ability to do work? (See Chapter 8 to review the scientific definition of *work.*)
6. How can mass be considered energy? Explain.
7. What famous equation describes the relationship between mass and energy?
8. What is the implication for the amount of energy stored in a small amount of mass, given the enormous value of the speed of light? How is it that just a few pounds of nuclear fuel can be enough fuel to provide the electric power of an entire city?
9. Are *all* forms of energy interchangeable? Explain.
10. How many energy conversions between different types of energies are there between the time a bungee jumper leaps off a tall bridge and the time he comes to a halt? What types of energy are involved? Is any energy actually lost?
11. Name some of the alternative energy sources being investigated by scientists that could perhaps meet future energy needs.
12. If only about 45% of the energy of the Sun reaches the surface of Earth, what happens to the other 55%?
13. What is the source of virtually all energy in the form of food and heat that we consume on this planet? Explain.
14. Think about your activities today. Pick one of them and identify the chain of energy that led to it. Where will the energy in that chain eventually wind up?
15. What are trophic levels? How much energy tends to be lost between levels and where does this energy go?
16. How efficient is a fourth-trophic-level predator in incorporating the energy of the Sun into its body tissue?
17. What does it mean to a scientist to say something is conserved? Give an example.
18. What is a system? How is this related to a conserved quantity such as energy?
19. What is the first law of thermodynamics?
20. Is energy ever completely lost and gone forever? Explain.
21. How old did Lord Kelvin estimate Earth to be? What was his reasoning behind the calculations? What was the flaw in his argument?
22. What is the ultimate origin of the energy in petroleum and coal? What are the implications for long-term energy use of continuing to rely on a high consumption level of fossil fuels?

## Questions

**1.** Two glasses of water, A and B, have the same temperature but contain different volumes of water (see figure). In which glass are the water molecules moving faster? Which contains more thermal energy? Which requires more heat to increase its temperature by 1°C?




**2.** A wooden block is released from rest at the top of a frictionless inclined plane and slides down to the bottom, as shown in the figure. What conversions of energy are taking place as the block slides down the inclined plane? What would your answer be if there were friction between the block and the plane?



**3.** You use energy to heat your home. What ultimately happens to the energy that you pay for in your heating bill?

**4.** What happens on a hot summer day when the energy demand on your local power plant exceeds its energy output?

**5.** Describe how you might convert the elastic potential energy of a coiled spring into thermal energy. How might you convert thermal energy into gravitational potential energy?

**6.** Plants and animals are still dying and ending up at the ocean bottom today. Why then, do we not classify fossil fuels as renewable resources?

**7.** Some people say that you lose more Calories by eating celery than you gain. How could that be?

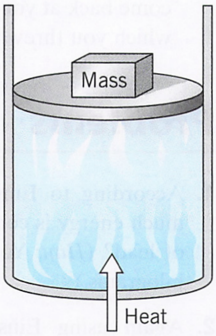
**8.** Many modern technologies are designed specifically to convert one kind of energy into another cheaply and efficiently. Photovoltaics, for example, convert light energy into electrical energy. Identify technologies that accomplish the following conversions:

a. chemical potential energy into light
b. electric potential energy into kinetic energy
c. elastic potential energy into sound
d. gravitational potential energy into kinetic energy
e. kinetic energy into elastic potential energy
f. mass into thermal energy
g. thermal energy into chemical potential energy
h. electric potential energy into chemical potential energy

**9.** Classify each of the following systems as either open or closed with respect to matter and with respect to energy. In each case do you have to qualify your answer in any way?

a. your body
b. a picnic lunch in a tightly shut Styrofoam cooler
c. a picnic lunch spread out on a blanket
d. your car
e. Earth
f. the Sun
g. Earth and the Sun

**10.** A cylinder with a movable piston contains a gas, as shown in the figure. A weight is placed on top of the piston. When 100 joules of heat is added to the gas, the internal energy of the gas increases by 50 joules and the piston rises, doing 75 joules of work. Does this process violate the first law of thermodynamics? Explain.




**11.** Suppose heat is added to a system, but the system does not expand. How much work is done by the system? The system could be anything, but for the sake of definiteness think of a gas in a rigid, closed container. Does the internal energy increase or decrease? Does the temperature increase?

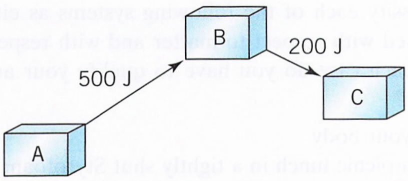
**12.** A closed, rigid container contains an ice-water mixture at 0°C. Heat is added slowly and some, but not all, of the ice melts. How much work did the system do? Did the internal energy increase or decrease? Did the temperature increase?

**13.** Suppose you compress a gas, doing 100 joules of work on the gas. If 100 joules of heat is allowed to escape during the compression, what is the change in internal energy?

**14.** A metal spoon is dropped into a shallow pot of boiling water and its temperature increases to 100°C. The heat added to the spoon is almost exactly equal to the increase in the spoon's internal energy. How much work does the spoon do in this process? Explain by using the first law of thermodynamics.

**15.** Two pieces of metal are identical in every way, except that one has a much larger thermal expansion coefficient. If equal amounts of heat are added to both pieces of metal, which metal does more work on its surroundings? Which metal's temperature increases more? Explain.

**16.** Three identical blocks exchange heat in the following way (see figure): A transfers 500 joules of heat to B and B transfers 200 joules of heat to C. Suppose the blocks do not expand or contract, so no work is done. Which block's internal energy increased the most? Which block's internal energy decreased? Why is it impossible for block C to transfer heat to block A?




**17.** Suppose you squeeze an air-filled hollow rubber ball in your hand. Assuming no heat escapes, what happens to the internal energy of the air inside?

**18.** If you throw a Wham-O SuperBall against a wall, it will come back at you with approximately the same speed with which you threw it. If you throw it at a wall that's moving toward you, the ball will come back with a faster speed. If the wall is moving away from you, the ball will come back with a slower speed. Using the SuperBall example as an analogy, explain why a gas tends to heat up when it is compressed and why it tends to cool when it expands. What is the relationship between compression, expansion, and thermodynamic work?

**19.** Heat always flows from an object at higher temperature to an object at lower temperature. Is it also true that heat always flows from an object with higher thermal energy to one with lower thermal energy? Explain.

**20.** A microwave oven is capable of raising the temperature of foods to over 100°C, despite the fact that no part of the oven in contact with the food reaches anywhere close to 100°C. What can you conclude about the mechanism responsible for raising the temperature of things you heat in the microwave? (*Hint:* Look at the first law of thermodynamics. What are the two ways you can change the internal energy of a thermodynamic system?)

# Problems

**1.** According to Einstein's famous equation, $E = mc^2$, how much energy is contained in a pound of feathers? A pound of lead? (*Hint:* You will first need to convert pounds into kilograms.)

**2.** Again using Einstein's equation, how much energy is contained in 0.001 g of matter? How about in 100 kg of matter?

**3.** Normally the energy expended during a brisk walk is 3.5 Calories per minute. How long (in minutes) do you have to walk in order to use up the Calories contained in a candy bar (approximately 280 Calories)? How long do you have to walk to produce the same amount of energy as a 100-watt light bulb that is lit for 1 hour? (*Note:* 1 Calorie = 1000 calories = 4186 joules.)

**4.** In order to lose 1 pound per week, you have to reduce your daily intake by 500 Calories per day. How long would you have to run in order to burn 500 Calories? (The Calories burned vary with the weight and intensity of the runner; assume you burn 7 Calories per minute.)

**5.** Sleeping normally consumes 1.3 Calories of energy per minute for a typical 150-lb person. How many Calories are expended during a good night's sleep of 8 h?

**6.** Above Earth's atmosphere we receive about 1400 W/m$^2$ of energy from the Sun. If you could convert 100% of this energy into usable electricity, how large a collecting area of solar cells would be necessary to produce a 1-gigawatt power plant?

**7.** In the Sun, 1 g of hydrogen consumed in nuclear fusion reactions produces 0.9929 g of helium; the other 0.0071 g of material is converted into other forms of energy.

a. How much energy does this process produce in joules?

b. How high could you raise the Mt. Palomar 5-m telescope ($4.5 \times 10^5$ kg) with this energy? (*Recall:* Work = Force [Newtons] × Distance [meters]; also remember the definition of *force* from Newton's law in Chapter 4.)

c. If you could convert 1 g of hydrogen into energy every second through nuclear fusion, the energy produced would be equivalent to how many 1-gigawatt power plants?

# Investigations

**1.** What kind of fuel is used at your local power plant? What are the implications of the first law of thermodynamics regarding our use of fossil fuels? Our use of solar energy?

**2.** Investigate the history of the controversy between Lord Kelvin and his contemporaries regarding the age of the Earth. When did the debate begin? How long did it last? What kinds of evidence did biologists, geologists, and physicists use to support their differing calculations of Earth's age?

**3.** Further explore the structure of trophic levels by looking up the various efficiencies with which different types of organisms use the energy from the level below it. Pay attention to what types of organisms are more efficient than others. What is it that makes them more efficient? What effect does being warm-blooded versus cold-blooded have on the efficiency with which organisms use energy, if any? What trophic level(s) do humans usually occupy, and what is the efficiency of the conversion of solar energy into human tissue?

**4.** Investigate possible sources of energy as alternatives to petroleum and coal. Make a list of alternative sources that are either being explored by scientists or are currently available, and evaluate the pros and cons of using each. What is the economic cost of switching to them? Should economics play the dominant role in deciding whether to use them, or should other considerations take precedence?

**5.** Investigate technologies that are being developed to exploit wind power. How do wind turbines work? Where are the best locations in the United States for wind farms? Why might some environmentalists raise objections to the construction of these energy-producing facilities?

**6.** New technologies using high-frequency sound (ultrasound) can be used to promote chemical reactions (sonication) or to produce light (sonoluminescence). Investigate these energy-conversion phenomena and their possible uses in science and industry.

**7.** Several different dieting strategies have been advocated by experts in recent years. For example, some nutritionists recommend avoiding carbohydrates, whereas others restrict fats and sweets. Nevertheless, all diets rely to some extent on reducing the amount of chemical potential energy in the food you eat (Calories) that is converted to chemical potential energy in your body (fat). Investigate one of these diets from the standpoint of the first law of thermodynamics.

**8.** North America boasts vast deposits of oil shale, a rock that holds a significant amount of petroleum in its pores. The total petroleum reserves in oil shale are estimated to be more than 500 billion barrels—at least 20 times the known reserves in all the world's oil wells. Investigate the pros and cons of exploiting this potential fossil fuel resource.

**9.** Identify four sources of energy around us that are constantly being renewed. What sources of energy do we use that are not constantly renewed?

## WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://www.nu.ac.za/physics/1M2002/Energy%20work%20and%20power.htm** An illustration of the metabolic equivalence of work and energy content in food.
2. **http://www.npg.org/specialreports/bartlett_index.htm** A discussion of the long-term exhaustion of fossil fuel use for energy production.
3. **http://history.hyperjeff.net/statmech.html** An annotated timeline of thermodynamics and a related topic called "statistical mechanics."